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REVIEW

Prioritizing weeds for biological control development in the western USA: adaptation of the Biological Control Target Selection system

Rachel L. Winston · Mark Schwarzländer · Hariet L. Hinz · Paul D. Pratt

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Abstract Nonnative invasive plants (weeds) negatively impact native biodiversity, ecosystem services, agriculture, and the economic interests and health of humans. Since 1902, biological weed control has been employed as a cost-effective and sustainable management option for weeds in the USA. However, biological control is not appropriate for all weeds, nor is sufficient funding available to develop biological control for all weed species. Researchers in South Africa recently developed a Biological Control Target Selection (BCTS) system as an objective, transparent, and simple approach to prioritizing weeds as targets for biological control. The system includes multiple attributes pertaining to the: (1) impact and importance of the target weed, (2) likelihood of achieving success, and (3) investment required to develop and implement biological control. Attributes are scored based on available literature, and the overall score for each weed is used to rank species according to their potential to result in successful biological control programs. This paper describes the adaptation of the BCTS for application to weeds in the western USA not already targeted for biological control.

Keywords Weeds · Invasive plants · Prioritization · Biological control of weeds · Biocontrol target selection

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R. L. Winston (✉)
MIA Consulting, Ogden, UT 84404, USA
e-mail: rachel@getmia.net

M. Schwarzländer
Department of Entomology, Plant Pathology and Nematology, University of Idaho, Moscow, ID 83844, USA

H. L. Hinz
CABI, 2800 Delémont, Switzerland

P. D. Pratt
USDA ARS, Invasive Species and Pollinator Health Research Unit, Albany, CA 94710, USA

Introduction

Non-native invasive plant species (hereafter weeds) have long been recognized as a significant threat to native biodiversity and ecosystem services (Pyšek et al. 2012; Vilà and Hulme 2017) and for their negative impacts to agriculture, forestry, infrastructure, and human health (Beck et al. 2008; Schaffner et al. 2020; Diagne et al. 2021). Injurious weed naturalizations outside their native range are likely to intensify with continuing globalization and international trade (van Kleunen et al. 2015). In the USA, weeds are frequently managed with herbicides or physical removal (van Driesche and Winston 2022). However,

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these conventional control methods are often nonviable over a prolonged period of time, and their feasibility is limited for the rugged, remote terrain and vast tracts of public lands with low agricultural value that constitute much of the western USA (Culliney 2005; Sheley et al. 2011). Classical biological control (hereafter biocontrol) of weeds is a cost-effective and sustainable management alternative and has resulted in some remarkable, long-term successes in a variety of environments (Schwarzländer et al. 2018; van Driesche et al. 2022). In the USA and its overseas territories, biocontrol has been utilized since 1902, resulting in 211 species of natural enemies released for the control of 83 weed species by the year 2020 (Winston et al. 2023).

Developing biocontrol is costly and generally relies on public funds because the development of safe and effective biocontrol agents is considered a public good (van Driesche and Winston 2022). With an ever-increasing number of weeds, deciding which species should be prioritized for biocontrol in a manner that offers the greatest likelihood of success and/or the greatest return of investment is paramount to maximize public resources. Historically in the USA, targets were selected based on expert opinion developed from experience with widespread species in the field and requests and funding from local resource managers. Over time, the approach became more sophisticated by utilizing expert opinion from local land managers, weed scientists, and biocontrol practitioners to rank potential weed targets according to their impact as well as the feasibility and likely success of a biocontrol program (Hansen and Bloem 2006; Raghu and Morin 2018). While there is substantial value in such approaches, there are also fundamental issues with relying so heavily on expert opinion and subjectivity. One is the potential bias of experts towards weeds of a familiar region or taxonomy (Kendig et al. 2022). A second problem is a lack of transparency for how some decisions were derived (Downey et al. 2021). Finally, both processes prioritized many weeds that had already been biocontrol targets in the region, in some cases for decades.

Researchers in South Africa have faced a similar need for improving and standardizing their biocontrol target prioritization process. They recently completed a review of 12 systems previously used to prioritize weed targets worldwide, comparing their attributes, methodology, outcomes, and inherent issues (Downey et al. 2021). The authors identified 13 attributes in these previous scoring systems, which they modified and used as the basis for developing a new prioritization process termed the Biological Control Target Selection (BCTS) system (Paterson et al. 2021). The BCTS system is populated with quantitative scoring of peer-reviewed literature and other published resources, resulting in an approach that is transparent, easily applied, adaptable to change, and that aligns the needs of funding bodies and researchers to produce a scientifically robust and defendable prioritization strategy (Paterson et al. 2021). South African researchers subsequently applied the BCTS system to all weeds regulated under the South African National Environmental Management: Biodiversity Act of 2004 (NEMBA) to produce a priority list of biocontrol targets for South Africa (Canavan et al. 2021).

This article describes the application of the South African BCTS system to regulated weeds in a 12-state-study area in the continental western USA that spans the authors' area of expertise, including Alaska, Arizona, California, Colorado, Idaho, Montana, New Mexico, Nevada, Oregon, Utah, Washington, and Wyoming (hereafter western USA). During the application of this system, several cases were encountered where the literature and data available for the western USA did not clearly fit the attribute definitions, cutoffs, and scores in the BCTS. Because the goals of this system are to be as transparent as possible and based on quantitative data, modifications were made to alter and more clearly define some BCTS attributes to ensure information available for the USA could be objectively categorized. The modified system has been validated through its application to all regulated plant species in the 12-state study area, the results of which are currently being summarized and will be presented elsewhere. This paper details and justifies all modifications to the BCTS system, and examples are provided.

Adaptation of the BCTS system

The system

In South Africa, the initial list for application of the BCTS system spanned the 379 weeds currently regulated under their NEMBA Act of 2004 as species that pose a threat to South Africa and require management

(Canavan et al. 2021). In the USA, there is no such equivalent. Although the Plant Protection Act of 2000 (7 U.S.C. 7701) regulates the introduction and interstate transport of federally designated invasive plant species, the current federal noxious weed list contains only 110 species (USDA APHIS 2010), many of which are not relevant to the 12-state study area. In the absence of a national comprehensive list of injurious regulated weeds, state noxious weed lists from the 12 western states of interest formed the backbone of the weed list for the USA adaptation of the BCTS. Weeds previously or currently targeted for biocontrol in the USA were subsequently removed, yielding a starting list of approximately 300 species.

The South African BCTS system has 13 attributes grouped into three sections: (1) the impact/importance of the target weed, (2) likelihood of achieving successful biocontrol, and (3) the investment required to implement biocontrol (Paterson et al. 2021). The same 13 attributes and three-section grouping were retained in the USA adaptation, but one additional attribute was added to the third section (Attribute 3B), and the possible scores were altered for select attributes (Table 1). For a full comparison of score definitions between the South African BCTS and the adaptation for the western USA, refer to Supplementary Table S1.

Similar to South Africa, the USA adaptation of the BCTS was populated with information acquired through a literature review. A quantitative scoring system was assigned to each attribute with the highest score indicating a greater priority for biocontrol. Each score was accompanied by a written rationale and references. Possible scores for each attribute are listed in Table 1. The overall score was calculated using the following formula:

$$\text{BCTS index} = (\Sigma \text{ Section 1}) \times [(\Sigma \text{ Section 2}) + (\Sigma \text{ Section 3})]$$

Table 1 Biological Control Target Selection (BCTS) system attributes originally developed for South Africa and changes (bold font) made during the adaptation for the western USA

Section	Attribute (South Africa)	Possible scores (South Africa)	Attribute (USA)	Possible scores (USA)
1. Impact/importance of the target weed	1A. Threat or impact posed by the target weed	1,2,4,6,8,10	1A. Threat or impact posed by the target weed	1,**4,7**,10
	1B. Geographic distribution	1,2.5,5,7.5,10	1B. Geographic distribution	**0,1,2,3,5,7,8,9,**10
	1C. Alternative control options	1,5,10	1C. Alternative control options	1,5,10
	1D. Conflicts of interest	1,5,10	1D. Conflicts of interest	1,**4,7**,10
2. Likelihood of achieving success	2A. Success elsewhere of biocontrol programs on the target weed	1,3,6,8,10,12,14,16,18,20	2A. Success elsewhere of biocontrol programs on the target weed	1,3,6,8,10,12,14,16,18,20
	2B. Ecosystem	5,10	2B. Ecosystem	5,10
	2C. Reproduction	5,10	2C. Reproduction	5,10
	2D. Habitat stability	5,10	2D. Habitat stability	5,10
	2E. Life cycle	5,10	2E. Life cycle	5,10
3. Investment required	3A. Uncertainty of weed origin or taxonomy	1,10	3A. Uncertainty of weed origin or taxonomy	1,10
			3B. Hybridization	**1,10**
	3C. Information on natural enemies	1,5,10	3C. Information on natural enemies	1,5,10
	3D. Sourcing agents	1,3,6,10	3D. Sourcing agents	**0,2,4,6,8,**10
	3E. Potential to find host-specific agents	1,10	3E. Potential to find host specific agents	1,**5**,10

For a full comparison of score definitions between the South African BCTS and the adaptation for the western USA, refer to Supplementary Table S1

The BCTS scoring formula was not changed for the USA adaptation and follows the same logic outlined in Paterson et al. (2021). Section 1 assesses the need for biocontrol. Weeds that are not problematic or that can be successfully controlled with other management techniques are given lower scores in this section. Such weeds should not be targeted with biocontrol even if there is a high chance of success (Section 2) and/or little investment required (Section 3). Section 1 prioritizes weeds that have significant negative impacts and lack effective alternative control methods, even if chances of biocontrol success are relatively low and significant investments are required. For this reason, the score for Section 1 is multiplied by the sum of the scores for Sections 2 and 3, increasing its weight in the final score. Section 2 assesses the likelihood of success of a biocontrol program while Section 3 assesses the investment required. Section 2 is considered somewhat more important than Section 3, which is reflected in the maximum score for Section 2 being ten points greater than that of Section 3. This approach assumes that greater investment is acceptable if the chances of controlling the target weed are high (Paterson et al. 2021). The minimum possible overall score for the USA adaptation of the BCTS system is 75 and the maximum is 4400, in contrast to the minimum possible overall score of 100 for the South African BCTS and the maximum of 4000.

Section 1: Impact and importance of the target weed

Section 1 assesses the target weed's status in the western USA. This includes its current impact, distribution, feasibility for control with methods other than biocontrol, and any conflicts of interest.

Attribute 1A: Threat or impact posed by the target weed

This attribute addresses negative consequences that might occur or are already present in the 12-state area, including environmental, economic, and social threats and impacts. The definitions of threat and impact utilized in Paterson et al. (2021) were retained, whereby threat indicates a possible exposure to harm, combined with the likelihood of that harm occurring, and impact is the actual effect that the weed has. Impact should be measurable and be demonstrated within the geographical area. Impacts should receive a higher score than threats, which may only be assumed and be based on impacts the weed has had elsewhere (Paterson et al. 2021).

For the creation of the BCTS in South Africa, the authors followed the impact classification system proposed by Blackburn et al. (2014), which is now referred to as the Environmental Impact Classification of Alien Taxa (EICAT). This system assigns an invasive species to one of five impact categories, including minimal, minor, moderate, major, or massive, based on evidence of impact via any one of 12 mechanisms. This system works well for weeds impacting native species or natural areas and was also utilized for such species in the USA adaptation. For agricultural weeds (species impacting crops and managed pastures), the BCTS uses impact ratings that had been previously assigned by a panel of experts (Zengeya et al. 2017). In the absence of a comparable ranking for agricultural weeds in the USA, an alternative method was devised based on Kendig et al. (2022), who developed an impact-rating system for both natural area and agricultural weeds threatening Florida, USA. Their system combines the EICAT approach with the Invasive Species Environmental Impact Assessment Protocol (Branquart 2009) and the Socio-Economic Impact Classification of Alien Taxa (Bacher et al. 2018).

For the USA adaptation, the impact categories created by Kendig et al. (2022) were modified to better align with the definitions used in the BCTS system (Supplementary Table S1). Because the intent of the USA adaptation was to prioritize biocontrol targets within the 12 western states, impacts reported elsewhere in the USA outside the 12-state area (or outside the USA) were given a lower score (1) compared to impacts documented within the study area. Weeds posing a threat or having negligible impacts on the native biota or abiotic environment, human well-being, or economic systems within the study area received a score of 4. Weeds with minor/moderate impacts (score 7) were defined as causing (1) declines in the performance (e.g., biomass, body size) or population size of native species, but no changes to the structure of communities or to the abiotic or biotic composition of ecosystems, or (2) income loss or changes in the size of social or economic activities with fewer people participating or accessing goods but the activity is still carried out. These changes to activities could be linked to accessibility to the activity area or minor/moderate effects to human health (e.g., contact dermatitis or allergies). Weeds with major/massive impacts (score 10) were defined as causing: (1) changes in the structure of natural communities or the replacement and local extinction of native species and/or changes in the abiotic or biotic composition of ecosystems, or (2) the disappearance of a social or economic activity from the area invaded by the target weed, a switch to other activities or abandonment of an activity without replacement, emigration from the region, or major/massive effects to human health (e.g., toxic fouling of a food or water source).

Attribute 1B: Geographic distribution

The geographic extent of a weed has important implications for determining if biocontrol is an appropriate management approach because it influences both the overall impact of the weed (Attribute 1A) and the likelihood of managing it successfully using other methods (Attribute 1C). Abundant and widespread weeds have greater negative impacts than weeds considered rare. Likewise, and as explained in Paterson et al. (2021), abundant and widespread weeds are often impossible to eradicate and more difficult to control using conventional control methods than weeds with small populations growing close together (Rejmánek and Pitcairn 2002).

For the BCTS system, the number of naturalized locations and the geographic pattern of locations are used as a proxy to indicate the weed's extent, and these are considered a reasonable predictor of the negative impacts the weed may have and potential benefits of using biocontrol instead of alternative control methods (Paterson et al. 2021). The BCTS scoring for this attribute first focuses on the number of naturalized localities of a target weed, assigning them to three categories: (1) less than ten localities—eradication may be possible with other control methods, (2) 10–50 localities—eradication is not possible, but effective control with other methods may still be achievable, and (3) more than 50 localities—biocontrol is required to play a significant role in reducing the invasiveness of the species because it is widely established. In recognition of spatially clumped infestations being more likely to be controlled using conventional control methods than geographically dispersed infestations (Panetta and Timmins 2004), the BCTS subdivides categories 2 and 3 according to the number of municipal areas or provinces in which the localities fall, respectively (Paterson et al. 2021).

For the USA adaptation, the BCTS scoring system was altered to account for the authority of county and state governments to control weeds (see Supplementary Table S1). Species not currently naturalized in the western USA received the lowest score (0) because control efforts are unnecessary. For naturalized weeds, ten was retained as the maximum number of localities where eradication with other control methods may still be possible. However, unlike the BCTS, geographic pattern was used to further split this category for the western USA because the location of even a small number of infestations can highly influence eradication efforts. Throughout the western USA, regulation and control of naturalized weeds are generally administered at the state level and enforced at the county level. Weeds distributed in only one county should have a higher probability of being eradicated due to being targeted by only one weed management entity, and they were therefore given a lower score (see Supplementary Table S1). Likewise, weeds occurring solely within one state have a much higher probability of control because they are managed by only one administrative agency. Widespread weeds that occur in more than one state were given higher scores to reflect the declining likelihood of their control across the entire region. The coordination of control efforts not only becomes increasingly difficult when more agencies are involved (Panetta and Timmins 2004), but many weeds in the western USA are also targeted for control in some states but not in others. For example, *Lepidium latifolium* L. (Brassicaceae) is listed for either prohibition or control in 11 of the 12 states included in this study. However, it remains unregulated in the state of Arizona, where the weed is naturalized. For weeds that occur in more than one state, higher scores were given to weeds with a greater number of localities because as the number of discrete infestations increases, the likelihood of spread increases (Panetta and Timmins 2004). As in the BCTS scoring system, expected spread of weeds was not included in this attribute or elsewhere in the USA adaptation because such data are not available for most weeds.

Attribute 1C: Feasibility of control with alternative methods

Attribute 1C assesses the feasibility of alternative control methods for weeds to prioritize species best suited for biocontrol and to exclude those weeds that should not be targeted by biocontrol. In the BCTS, several variables are analyzed when scoring this attribute, including the availability of alternative control methods, plant growth traits that influence the efficacy of alternative control methods, infestation traits that influence the efficacy of alternative control methods, the number of naturalized localities, and existing control or eradication programs (Paterson et al. 2021). For the western USA, only some variables could be included in the same manner. The majority of weed species listed as noxious for the western USA have herbicides registered within the region and/or published literature for physical and mechanical removal. Consequently, the availability of alternative control methods was not used when scoring USA weeds. The growth form of the weed, however, was retained as essential in the scoring of this attribute for the western USA. As explained in Paterson et al. (2021), the decision on control method is highly dependent on the species growth form because target weeds with particular traits can be difficult or impossible to control with conventional methods. These traits include creeping and rooting stems, epiphytes, rhizomes or tubers, submerged aquatic plants, trees/shrubs with suckering roots, and vines. These traits were retained for the USA adaptation, and parasitic plants were added because they grow embedded within and intertwined with host plants and are difficult to impossible to treat or remove without damaging the host plants.

Infestation traits can also influence the feasibility and/or efficacy of alternative control methods for a weed. The BCTS analyzes the habitats and locations invaded by weeds, recognizing that some habitats are not suitable to conventional control operations due to inaccessibility (e.g., high-altitude mountainous habitats) or ecological sensitivity (e.g., communities in which potential non-target effects are unacceptable) (Paterson et al. 2021). This approach cannot be easily applied to the western USA. Most weed distribution databases available for the study area (e.g., https://www.inaturalist.org/, https://www.gbif.org, and https://www.eddmaps.org/distribution/index.cfm) do not include physical or ecological site data along with weed distribution data. More importantly, most weeds in the western USA occur in a variety of habitats and geographic locations and cannot be cleanly categorized into one or another. For example, the weed *Isatis tinctoria* L. (Brassicaceae) is established in ten of the 12 western states in the USA. In California, *I. tinctoria* is considered a threat to the federally endangered *Phlox hirsuta* E.E. Nelson (Polemoniaceae), endemic to Siskiyou County, California (USFWS 2006). Conventional control methods cannot be used to control *I. tinctoria* in this region because they are currently listed as threats to the recovery of *P. hirsuta* (USFWS 2006). Concurrently, *I. tinctoria* infestations elsewhere in the western USA are regularly treated with a range of chemical, mechanical, and physical methods (DiTomaso et al. 2013). Consequently, accessibility and ecological sensitivity were not considered when scoring this attribute for the USA.

Infestation size is another important factor influencing the feasibility and efficacy of alternative control methods (Rejmánek and Pitcairn 2002). This trait was discussed in Paterson et al. (2021) but is not included in the BCTS scoring for Attributes 1B or 1C. Because this information is not included in most weed distribution databases available for the USA, this trait was also not included in the adaptation for the western USA.

As explained in Paterson et al. (2021), if eradication of a target weed is possible, biocontrol should not be considered until all attempts at eradication have failed. In the BCTS, eradication is considered a possibility only for weeds with less than ten localities. In this manner, geographic distribution is essentially counted twice—in Attribute 1B and again here for 1C. This is intentional because of the importance of excluding any weed that can be successfully eradicated from consideration for biocontrol. This approach was retained for the USA adaptation with minor changes. In the BCTS, the location and geographic pattern of the ten or fewer localities are considered less important for the possibility of eradication (Canavan et al. 2021). However, in the western USA, weeds located solely within one county or one state have a much higher probability of being eradicated (see explanation under Attribute 1B). Consequently, weeds with ten localities or less across more than one state were not considered to have a high possibility of eradication.

In the BCTS, weeds with ten localities or less are further analyzed according to growth form and habitat, as described above. In addition, the literature is searched to determine if an eradication plan has been implemented or is being investigated for those weeds (Canavan et al. 2021). As described in Attributes 1B and 1D, there is no weed eradication program at the national level in the USA. However, state programs target select weed species for eradication. For the USA adaptation, weeds were considered possible to eradicate if all western states in which they are naturalized have listed them as eradication targets. This differs from the BCTS in that all weeds were considered in this variable, not only those with ten localities or less. For example, *Echium plantagineum* L. (Boraginaceae) is currently naturalized at 14 localities across two states (California and Oregon) and is targeted for eradication in both states.

For the USA adaptation, weeds established in more than one state (scores 5–10 in Attribute 1B) and weeds established within one state but with more than ten localities (score 3 in Attribute 1B) were assessed with regard to their growth form. Those with traits identified as reducing the efficacy of alternative control methods were assigned the highest score (10). Widespread species without plant traits deemed difficult to control with alternative methods received an intermediate score (5). For such species, biocontrol may still be pursued, but it may not always be necessary because at least partial control of these weeds can be achieved using other control methods. Weed species occurring only in one state and with ten localities or less (scores 1 and 2 in Attribute 1B) were assessed with regard to their growth form. Those without plant traits deemed difficult to control with other methods received the lowest score (1). Any infrequent, clumped species with plant traits difficult to control by other means received an intermediate score (5): although their current distributions may be limited, the difficulty of controlling these species suggests spread is likely, and biocontrol may be necessary to help limit future populations. Weeds targeted for eradication by all states where they currently occur were assigned the lowest score (1), regardless of the number of naturalized localities, because eradication is possible for these species. Species currently established in the USA but outside of the 12 western states were also assigned the lowest score (1) because such weeds should not be targeted for biocontrol on behalf of the western USA.

Attribute 1D: Conflicts of interest

Conflicts of interest can arise if a weed targeted for control is perceived as detrimental by some and beneficial by others. Biocontrol, in particular, may amplify these conflicts of interest because of the irreversibility of the actions of introduced biocontrol agents. Conflicts of interest have delayed and even halted biocontrol programs, for example pushback from the beekeeping industry once halted biocontrol efforts against *Centaurea solstitialis* L. (Asteraceae) in the western USA (Turner 1985). Attribute 1D evaluates current perceptions of weeds to identify conflicts of interest that may arise if biocontrol is pursued. The key component of this attribute in the BCTS is the NEMBA Act of 2004 which legislates a wide range of activities prohibited nationally for listed species, thus eliminating or reducing conflicts of interest resulting from their control (Paterson et al. 2021).

In the USA, the Plant Protection Act (2000) grants authority to the United States Department of Agriculture's Animal and Plant Health Inspection Service to prevent the importation or interstate transport of federally listed noxious weeds without a valid permit. However, many components of the Act are not enforced, and the current federal noxious weed list is not a comprehensive representation of weed species threatening the economic and ecological integrity of the USA (Reichard and Hamilton 1997). As stated above, individual states have authority to regulate the entry, distribution, and cultivation of weeds within their jurisdiction, and several western states have strict noxious weed laws enforced at both the state and county level (Westbrooks 1998). However, the sovereignty of states with regard to their noxious weed regulations and management can confound weed categorizations and introduce additional conflicts of interest. For example, *Clematis orientalis* L. (Ranunculaceae) is listed as a Class A noxious weed in Washington state, meaning that introduction to the state is prohibited and eradication of established populations is required by law. This species is not included on noxious weed lists of other northwestern states, and *C. orientalis* can be legally moved and propagated in states bordering Washington. There are no conflicts of interest for controlling this species in Washington. However, the species is currently available for purchase from horticultural growers in nearby states, creating a potential conflict of interest. This example illustrates the complexity of categorizing weed conflicts of interest in the western USA, and this is reflected in the scoring options for this attribute.

Plants grown intentionally for food, forage, turfgrass, wildlife shelterbelts, site reclamation, or that provide critical resources to valued species are recognized as economically or ecologically important in the USA, and these started with the lowest score (1) to indicate that biocontrol of these species would likely generate conflicts. If the scoring of other attributes suggests that one of these species is a high priority for biocontrol, the species should still be considered, and resolution of the conflicts of interest should be part of any resulting biocontrol program (Paterson et al. 2021). In some cases, economically important weeds spread primarily by seed, but seeds/fruit are not what makes these species economically important. This is the case for *Elaeagnus angustifolia* L. (Elaeagnaceae), an outcrossing species valued by landowners as a shade tree, windbreak, and for erosion control (Collette and Pither 2015) but that is also listed as noxious in seven western states. This and similar species could still be prioritized for biocontrol that targets their reproductive structures to reduce their spread without harming the economic product (Paterson et al. 2021). Such species received an intermediate score (4) in the USA adaptation.

Horticultural species are particularly difficult to categorize by potential conflicts of interest. The horticulture industry is a significant source of invasive plant introductions in the USA, including those made via nurseries, explorations on behalf of botanical gardens and arboreta, garden club and horticultural society plant exchanges, and the seed trade (Reichard and White 2001). In a study of the 235 woody plant species that have naturalized outside of cultivation in North America, 82% had been used in landscaping, and an additional 3% had been widely distributed for soil erosion control after having been initially grown as ornamentals (Reichard and Hamilton 1997). Nurseries continue to offer plant species listed as noxious either federally or in select states. While it is illegal to distribute listed species to or within locations where they are prohibited (Westbrooks 1998), it is up to nurseries to know and comply with laws (Reichard and White 2001), and many nurseries continue to ship species to prohibited locations in ignorance or defiance of regulations. Although it is recognized that horticultural species have economic value in the USA (Parrella et al. 2015), and that biocontrol of these species may generate conflicts, they received a higher score (7) compared to plant species grown intentionally for food, forage, turfgrass, wildlife shelterbelts, site reclamation, or that provide critical resources to valued species. Weedy plants grown in personal gardens for their herbal or culinary value were included in this level (Reichard and White 2001). Noxious weeds used for pollinator services were also included in this level because they are either ornamentals and/or are weedy species not intentionally grown for pollination services. Target weeds without any indication for conflicts of interest, such as agricultural weeds, species prohibited federally or by most states in the western USA, and species not established in the USA but listed as prohibited, were given the highest possible score (10). For this attribute, potential conflicts of interest identified anywhere in the USA were considered.

Section 2: Likelihood of achieving success

Section 2 addresses the likelihood of the weed target being successfully controlled with biocontrol by focusing on attributes that are considered good predictors of a successful biocontrol program. These include outcomes for biocontrol of the weed or its congeners elsewhere and plant traits associated with higher biocontrol success rates.

Attribute 2A: Success of biocontrol programs elsewhere

This attribute is based on the premise that a biocontrol agent released successfully against a weed in a given country might also be successful if released in a new country (Harris 1973). In addition, costs associated with such a biocontrol agent will be lower as aspects of the biology are already known and release methods already determined (Paynter et al. 2015). Consequently, approved biocontrol agents that have successfully controlled the target weed elsewhere should be prioritized when new biocontrol programs are initiated in novel locations for that weed (Paterson et al. 2021). Conversely, some biocontrol agents never established following releases, or they never contributed appreciably to the control of the target weed. For example, between 1963 and 1982, nine releases of *Altica carduorum* Guérin-Méneville (Coleoptera: Chrysomelidae) were attempted on *Cirsium arvense* (L.) Scop. (Asteraceae) in five countries, but all releases failed to establish (Winston et al. 2023). Releases of ineffective agents should be avoided because they accrue substantial costs for their development while providing no benefits, and their release into a novel environment introduces non-zero risks for non-target effects (McClay and Balciunas 2005). According to Paynter et al. (2009), another predictor for the odds of successful biocontrol is the successful control of a closely related species. This is based on the assumption that phylogenetically related plant species have similar traits, plant–herbivore interactions, and host-range patterns of associated natural enemies (Wapshere 1974).

Attribute 2A analyzes the success or failure of weed biocontrol programs conducted elsewhere, and the resource used for the assessment is the online, updated version of 'Biological Control of Weeds: A World Catalogue of Agents and Their Target Weeds' (hereafter catalog) (Winston et al. 2023). In the catalog, each biocontrol release made worldwide is assigned an impact rating of heavy, medium, variable, slight, none, or unknown. For both the BCTS and the USA adaptation, the scoring of this attribute reflects those ratings (see Supplementary Table S1). In both the original BCTS and the USA adaptation, the highest score (20) was given to target weeds that have had successful biocontrol elsewhere and that also have congeners with successful biocontrol. The lowest score (1) was given to weeds that have been targeted for biocontrol but without success. For the USA adaptation, unsuccessful programs were defined as those where all agents released worldwide either failed to establish or they have had no measurable impacts on their target weed(s). A score of 6 was given to biocontrol programs where impacts were rated as unknown, which could be due to: (1) a lack of post-release monitoring, (2) the program being compromised post-release, or (3) the release having been made too recently for impacts to be measurable. Novel weed targets were included in this level because biocontrol may or may not be successful, and this grouping ensures they are not underestimated compared to weeds with existing programs elsewhere (Paterson et al. 2021). The subsequent levels of this attribute pertain to slight (10), medium (14), and heavy impacts (18), sequentially. In the BCTS, variable impacts are grouped with slight impacts (Paterson et al. 2021). In the catalog, variable impact is often assigned to biocontrol releases that resulted in heavy impact in some regions, climates, habitats or seasons but had no or low impact in others. Because the average of this impact category could be described as medium, variable impacts were lumped with medium impacts for the USA adaptation.

Each impact category in this attribute is accompanied by an adjacent level with a higher score given if the target weed in that impact category also has congeners that were successfully controlled with biocontrol (see Supplementary Table S1). For the USA adaptation, successful biocontrol was defined as the release of any biocontrol agent worldwide that resulted in slight, variable, medium, or heavy impacts on its target weed(s). Slight, variable, and medium impacts were intentionally included in this definition because some biocontrol agent impacts can vary significantly among countries, especially when there are differences in climate, habitat, genetic variability in hosts and/or agents, etc. (Harms et al. 2020). For example, *Microlarinus lareynii* (Jacquelin du Val) and *M. lypriformis* (Wollaston) (Coleoptera: Curculionidae) were released for the control of *Tribulus terrestris* L. (Zygophyllaceae) in the continental USA in 1961 (Maddox 1976). The weevils have generally proven ineffective at higher elevations and latitudes where cold winter temperatures cause high weevil mortality (Winston et al. 2023). However, beetles collected in the continental USA were subsequently released in Hawai'i (Maddox 1976) where they successfully controlled *T. terrestris* on some islands (Winston et al. 2023).

The catalog contains information on four categories of biocontrol agents: (1) classical releases of biocontrol agents introduced from outside the country of release, (2) native natural enemies utilized in augmentative releases, (3) natural enemies unintentionally introduced to novel countries, and (4) bioherbicides. In the BCTS, catalog categories 1–3 are considered for this attribute. For the USA adaptation, categories 2 and 3 were excluded because most species within those categories were never formally tested or approved prior to their augmentative use or unintentional introduction within a country. Because the evaluation of biocontrol programs elsewhere is considered the best predictor of successful biocontrol (Paterson et al. 2021), this attribute was given a higher total score (20) compared to other attributes in this section (10), thus ensuring its higher weight in the overall score.

Attribute 2B: Ecosystem

While there are several North American examples of terrestrial weeds being successfully controlled with biocontrol (e.g., *Linaria dalmatica* (L.) Mill. (Plantaginaceae) (Sing et al. 2022)), a recent analysis of weed biocontrol releases worldwide through 2012 corroborated earlier reports (Paynter et al. 2012) that aquatic and wetland weeds have a higher probability of successful biocontrol compared to terrestrial weeds (Panta et al. 2024). Attribute 2B scores weeds according to ecosystem, with aquatic (emergent, floating, or submerged) and wetland weeds (plants that primarily grow in areas subject to regular seasonal flooding) receiving a higher score (10) compared to terrestrial weeds (score 5). The scoring and rationale of this attribute remained unchanged from the BCTS (Paterson et al. 2021).

Attribute 2C: Plant reproduction

Plants reproducing sexually have long been deemed difficult to manage via biocontrol because of their genetic variation (Burdon and Marshall 1981). However, there are many exceptions to this, such as the successful biocontrol of the outcrossing *Centaurea diffusa* Lam. (Asteraceae) in western Canada (Myers et al. 2009). Paynter et al. (2012) and Panta et al. (2024) found that weeds which reproduce only asexually have a higher probability of control compared to those capable of reproducing sexually. For the BCTS, weeds that can only reproduce vegetatively or by apomixis receive a higher score (10) than weeds that can reproduce sexually (score 5). The scoring and rationale were retained for the western USA. Some weeds reproduce only asexually in the USA although they are capable of sexual and asexual reproduction in the native range (e.g., *Poa bulbosa* L. (Poaceae) (DiTomaso et al. 2013)), and other weeds are capable of both forms of reproduction in the western USA but typically reproduce asexually (e.g., *Azolla pinnata* R.Br. (Salviniaceae) (DiTomaso et al. 2013)). In line with the BCTS, these weeds were given the higher score to denote their predominantly asexual reproduction in the western USA.

Attribute 2D: Habitat stability

The successful establishment and population increase of biocontrol agents has been positively correlated with habitat stability (Hall and Ehler 1979). Conversely, regularly disturbed habitats such as annual crops and improved pastures have been deemed less amenable to biocontrol (Julien 1989) because they are less likely to support adequate biocontrol agent populations. For example, the biocontrol agent *Zygogramma suturalis* (Fabricius) (Coleoptera: Chrysomelidae) causes extensive damage to its target *Ambrosia artemisiifolia* L. (Asteraceae) in stable, undisturbed locations in Russia. However, beetle densities in adjacent annual crop habitats are insufficient to suppress the target weed (Reznik 1996). In the BCTS, Attribute 2D addresses habitat stability by assigning a lower score (5) to weeds that predominantly occur in cultivated land and improved pastures. The scoring and rationale of this attribute were unchanged for the USA adaptation (see Supplementary Table S1). Some weeds in the USA are problematic in crops and improved pastures as well as open rangelands or natural areas (e.g., *Bromus tectorum* L. (Poaceae) (DiTomaso et al. 2013)). These weeds were scored according to the predominant habitat in which most negative impacts have been reported in the western USA. If none of the habitats are predominant, the higher score was assigned, assuming sufficient weed populations occur in undisturbed habitats to sustain biocontrol agent population increase.

Attribute 2E: Life cycle

Rea (1998) stated that weeds most susceptible to biocontrol are short-lived herbaceous plants that invest directly into reproduction and spread, while perennial woody species have a greater capacity to withstand herbivory and disease by drawing on storage reserves. In contrast, Paynter et al. (2012) and Panta et al. (2024) found that annual weeds are associated with a lower probability of successful biocontrol compared to biennial and perennial species. Biocontrol of annual weeds can be successful, especially when biocontrol agents reduce seed production within a single growing season. For example, *Mogulones larvatus* (Schultze) (Coleoptera: Curculionidae) and *Longitarsus echii* (Koch) (Coleoptera: Chrysomelidae) caused a significant decline of the winter annual *Echium plantagineum* L. (Boraginaceae) in Australia (Sheppard and Smyth 2012). There are numerous examples of the successful biocontrol of perennial species, including large trees (e.g., the suppression of *Melaleuca quinquenervia* (Cav.) S.T. Blake (Myrtaceae) in Florida (Smith et al. 2024)). In line with the BCTS, Paynter et al. (2012), and Panta et al. (2024), annual weeds received a lower score (5) for Attribute 2E compared to biennials or perennials in the western USA (score 10). Some weeds have an annual, biennial, or perennial life cycle in the USA, depending on environmental and habitat conditions. These weeds were scored according to the predominant life cycle documented in the habitat where they are considered most problematic in the western USA.

Section 3: Investment required

Developing new classical weed biocontrol agents for the USA is a lengthy and expensive process (van Driesche and Winston 2022). If costs are exceedingly high, programs can exhaust their funding and fail, as was the case for *Senna obtusifolia* (L.) H.S. Irwin and Barneby (Fabaceae) in Australia (Palmer 2012). Section 3 of the BCTS assesses investments required for a biocontrol program and prioritizes (higher scores) less expensive programs. The attributes in this section pertain to steps considered limiting factors in the implementation of a biocontrol program. In some instances, comparatively expensive biocontrol programs have produced spectacular successes and economic savings (e.g., the control of *Cylindropuntia* and *Opuntia* spp. in Australia (Julien et al. 2012)), demonstrating expensive programs should not be discounted outright. To account for this, the BCTS formula gives greater weight to Section 1 (negative impacts of the weed) and slightly more weight to Section 2 (chances of success) compared to Section 3.

Attribute 3A: Uncertainty of weed origin or taxonomy

Uncertainty regarding the taxonomic status or native distribution of a weed often requires genetic research to ensure the correct organism and location are being searched for biocontrol candidates (Gaskin et al. 2011). Such studies increase the time and cost of a biocontrol program and are assessed in Attribute 3A. The taxonomic status of weeds is regarded as uncertain when (1) they are the result of artificial selection that has created hybrid cultivars which naturalized in the USA but that do not occur elsewhere in wild populations, or (2) the taxonomic delimitation is unclear and could have biological implications impairing the search for biocontrol candidates. For scenario 1, sourcing suitable biocontrol candidate populations for hybrid cultivars could be problematic because herbivore populations adapted to these cultivars may not exist. The complicated horticultural history of *Lantana camara* L. (Verbanaceae) has resulted in a cryptic systematic complex of cultivars (Sanders 2006) that has impaired biocontrol efforts because out of the many agents released worldwide, most are specific to only one or two cultivars, and large-scale control of the weed has not been achieved (Paterson et al. 2021; Winston et al. 2023). For scenario 2, ambiguity in taxonomic delineation can lead to exploration of an incorrect plant species in the native range or the collection of biocontrol candidates that readily attack the ambiguous species in the native range but not the biotypes present in the invaded range. For example, the *Pilosella* spp. complex consists of species, subspecies, and aggregates whose frequent interspecific and introgressive hybridizations make finding stable weed populations difficult in the native range of Europe and the invaded range of the Pacific Northwest (Moffat et al. 2015). This further complicates the search for potential biocontrol agents because some natural enemies can readily differentiate between *Pilosella* spp. (Moffat et al. 2015) and may not accept novel hybrid combinations present in North America. Knowledge of the correct region of origin is also necessary for identifying effective biocontrol agents, as exemplified by the *Chromolaena odorata* (L.) R.M.King & H.Rob. (Asteraceae) system reported by Zachariades et al. (2011).

The BCTS includes a third scenario for this attribute that warrants a lower score—the naturalization of hybrids formed between weeds and native congeners in the invaded range. The rationale is this scenario may result in homogenization and potential non-target effects from biocontrol agents, an additional risk factor that would require more extensive host-specificity testing in quarantine (Canavan et al. 2021). For the USA adaptation, this scenario was elevated to a new attribute (Attribute 3B).

Attribute 3B: Hybridization

This attribute was added to the USA adaptation of the BCTS (see Attribute 3A above). Weeds documented hybridizing with congeners native to the USA (e.g., *Myriophyllum spicatum* L. hybridizing with the native *M. sibiricum* Kom. (Haloragaceae) (Glisson and Larkin 2021)) as well as with species of economic importance to the USA, regardless of being congeneric (e.g., *Aegilops cylindrica* Host (Poaceae) hybridizing with winter wheat, *Triticum aestivum* L. (Poaceae) (Mallory-Smith et al. 2018)) were assigned lower scores (5) compared to weeds with no such hybridization documented (score 10). When scoring this attribute, any hybridization with a native or commercially important species occurring anywhere in the USA was included.

Attribute 3C: Information on natural enemies

Having prior knowledge about natural enemies associated with a plant targeted for biocontrol can greatly reduce program costs. If the biology and ecology of a biocontrol candidate are also known, this further improves the probability of successfully rearing and testing the candidate species. In the BCTS, weeds with substantial literature on the identity and biology of associated natural enemies receive the highest score in this attribute (10), and those with no available information receive the lowest score (1). Weeds with published information on natural enemies but that lack biological and ecological information of prospective biocontrol agents receive an intermediate score (5), for example, see Francis et al. (2009) for a comprehensive list of natural enemies of *Hesperis matronalis* L. (Brassicaceae). The scoring and rationale of this attribute were unchanged from the BCTS. However, more details were added to the USA definitions to more clearly separate the high and intermediate scores. Some research on natural enemies (score 5) was defined to include: (1) biocontrol surveys in the native range, (2) literature reviews of known natural enemies, (3) host-specificity testing/life cycle studies conducted on prospective agents of the target weed that were subsequently never released, and/or (4) host-specificity testing conducted on weeds other than the target for which the target weed was included in trials. Substantial research on natural enemies (score 10) was defined to include: (1) a prospective agent that has already been formally approved and/or released outside of the USA and/or (2) a prospective agent that has undergone host-specificity testing outside of the USA but has not yet been approved and/or released, provided the program is still active. Studies involving pathogens were included in the USA adaptation, but only those not considered for application as bioherbicides.

Attribute 3D: Sourcing agents

This attribute assesses the feasibility of, and amount of effort required for, obtaining prospective biocontrol agents. For some weeds, biocontrol agents may have already been developed, released, and established elsewhere, and minimal effort should be required to transfer these to USA research facilities. For weeds without biocontrol programs, the weed's native range must be surveyed for biocontrol candidates, and promising species must be exported via the proper legal channels to the USA or external collaborative research facilities. This stage of a biocontrol program is often limiting and can greatly hinder potential success (Paterson et al. 2021) because the countries or regions in which a weed is native may be unsafe or inaccessible for researchers from or on behalf of the USA. Even if they are accessible, countries may lack research infrastructure to assist with survey efforts. Another potential impediment concerns the export of prospective biocontrol agents. The 1993 Convention on Biological Diversity (CBD) and the 2014 Nagoya Protocol [on the Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from their Utilization] have changed how biocontrol agents can be accessed (Silvestri et al. 2020; Mason et al. 2023). Pursuant to these agreements, several countries have adopted access and benefit sharing (ABS) regulations that have increased the bureaucratic burden and resources needed to obtain permits, or in extreme cases, hindered the export of genetic resources altogether (Silvestri et al. 2020). In addition, other international regulations (e.g., the Convention on International Trade in Endangered Species of Wild Fauna and Flora, CITES) and national regulations (e.g., protected areas or species) may apply and must be considered before surveys for prospective biocontrol agents can be conducted.

In the BCTS, safety, infrastructure, and presence of biocontrol research facilities were evaluated for each weed's native range to score the level of effort required to source prospective biocontrol agent populations. For the USA adaptation, emphasis was placed on overall accessibility, existing research infrastructure, and ABS regulations, and greater detail was added to definitions to more clearly separate attribute scores (see Supplementary Table S1). Inaccessible countries were defined as those considered unsafe for travel or that are restricted to researchers from or on behalf of the USA for socio-political reasons. Accessible countries were those not defined as inaccessible. Countries with limited research infrastructure were defined as those lacking active biocontrol laboratories. Although cooperators in countries with no biocontrol laboratory can greatly facilitate in-country efforts, relationships often depend on individual collaborators, which are frequently subject to change. Consequently, the presence of a biocontrol laboratory was deemed a better surrogate for the existence of effective cooperators. ABS regulations can vary significantly between countries but were over-simplified in the USA adaptation into two categories: (1) countries that are Party to the Nagoya Protocol and that have implemented ABS regulations or are known to be developing or revising their ABS regulations, and (2) countries that are not Party to the Nagoya Protocol and/or countries that are Party but have no ABS regulations in place or known to be under development and/or countries that do not restrict access to their genetic resources. The data to assess this were derived from the Access and Benefit-Sharing Clearing-House (Convention on Biological Diversity 2023).

For the USA adaptation, the lowest score (0) was assigned to weeds for which the native range is inaccessible, the native distribution is unknown, or the export of genetic resources is not possible. In the BCTS and the USA adaptation, plants with unknown native distributions receive low scores from this attribute and Attribute 3A (uncertainty of weed origin or taxonomy). This compounding scoring is intentional because not knowing the target weed's native distribution is a major obstacle in a biocontrol program (Paterson et al. 2021). In the USA adaptation, the next lowest scores (2 and 4) were assigned to weeds native to countries with ABS regulations in place. These were separated based on the presence of an active biocontrol facility. The next two scores (6 and 8) were assigned to weeds native to at least one country with no ABS regulations in place or where access to genetic resources is not restricted. These were again separated based on the presence of an active biocontrol facility. In this manner, the absence of ABS regulations was given more weight (higher scores) than countries with active biocontrol facilities. The highest score (10) was assigned to weeds for which a biocontrol research unit has a culture or easy collection source of the potential agent(s) and ABS regulations are not in place or where access to genetic resources is not restricted. For such agents, collection trips do not need to be made to the native range. This score included biocontrol agent populations that have established elsewhere with at least slight impacts in the field, have been confirmed as established elsewhere but it is too early to determine impacts, or have been approved and/or released but not yet confirmed as established, however a population is being maintained in quarantine.

Attribute 3E: Potential to find host-specific agents

The most common reason candidate biocontrol agents are rejected during investigations is that the species is insufficiently host-specific (Paterson et al. 2021). Plants closely related to a weed are more likely to be used as alternate hosts than are distantly related plant species (Hinz et al. 2019), with congeners accounting for the majority of non-target attack (Pemberton 2000). Weeds with few or no native or economically important congeners should be at least risk of having prospective biocontrol candidates rejected due to host-specificity concerns (Suckling and Sforza 2014). Weeds with native congeners or economically important relatives can, however, still have host-specific biocontrol agents (Paterson et al. 2021). For example, *Phrydiuchus tau* Warner (Coleoptera: Curculionidae) was released on *Salvia aethiopis* L. (Lamiaceae) in the western USA, despite having dozens of native and ornamental congeners established in the country.

High weevil populations have contributed to the control of *S. aethiopis* in parts of California, Idaho, and Oregon (Winston et al. 2023), without any reported non-target attack (Hinz et al. 2019). This attribute is intentionally not weighted heavily in the BCTS so as not to outright reject weeds with native or commercially important congeners.

The scoring and rationale of the highest and lowest levels of this attribute were unchanged in the USA adaptation. However, an intermediary level was added to account for ornamental species, as discussed in Attribute 1D (conflicts of interest). Introduced ornamental plant species received an intermediate score, recognizing their commercial importance to some, but with a higher score in order to decrease their weight compared to native congeners and congeners grown commercially as food or fodder species. When scoring this attribute, any native or commercially important congeners present anywhere in the USA were included. Congeners that have been targeted for biocontrol in the USA (e.g., the ornamental *Cytisus scoparius* (L.) Link (Fabaceae)) were not considered economically important in this attribute.

Conclusions

The BCTS was designed for two purposes (Paterson et al. 2021). The first was to develop a system for the prioritization of South African biocontrol targets that was easily applied, adaptable, transparent, and that addressed stakeholder needs while fulfilling regulatory demands. The second purpose was to build on the strengths of previous prioritization efforts worldwide and provide a procedural template that could be modified or adopted elsewhere. The research teams in South Africa succeeded with both objectives. The USA adaptation is, to the authors' knowledge, the first attempt to adjust the BCTS framework for use in a different region. The BCTS system proved relatively easy to adapt for the western USA, and most modifications described in this article account for the differences in weed regulations, management approaches, and literature and distribution data available that exist between the two countries. An obvious strength of the BCTS is that attribute scoring is based on published information, which increases objectivity compared to evaluations based solely on expert opinion. Attribute levels are defined as clearly as available data allows, and each weed's scores are supported by published references, thus maintaining transparency for how scores and rankings are derived. All stakeholders in the western USA will be able to follow how the most suitable biocontrol candidates were identified and why some problematic weeds are not, and should not, be targeted for biocontrol.

The BCTS is a data-driven assessment and was designed to be a dynamic system that changes as different/additional data becomes available (Paterson et al. 2021). For both South Africa and the western USA, a lack of data is a limiting factor for the scoring of some attributes. As more literature becomes available, the system will improve, and overall ratings will be strengthened. Likewise, if new data becomes available, additional attributes may be added to the framework (e.g., the size, habitat, or geographic characteristics of existing weed infestations).

Some of the existing gaps in the BCTS are due to insufficient financial resources. In their analysis of successful weed biocontrol programs, Paynter et al. (2012) found the three best predictors of biocontrol impacts include a weed's mode of reproduction (sexual or asexual), ecosystem (aquatic/wetland versus terrestrial), and whether it was reported to be a major weed in its native range. While the first two predictors are already included in the BCTS in Attributes 2C and 2B, respectively, the third was intentionally omitted due to the large amount of research required (Downey et al. 2021). It was omitted from the USA adaptation for the same reasons, but it should be added to future updates to improve the framework if resources become available.

The prioritization framework could also be expanded to include new attributes not considered in the BCTS. For example, the biocontrol prioritization tool utilized in New Zealand was recently modified and updated (Paynter and McGrannachan 2021) to include a new statistical technique for modeling potential biocontrol impacts as well as a new system to score weed impacts. The latter takes into account the invasive ability of a weed, the number of different habitats impacted, and socio-political pressure to control the weed, among other variables (Paynter and McGrannachan 2021). These improvements and additions may be considered for inclusion in future updates of the BCTS should the supporting data become available.

The successful adaptation of the BCTS in the western USA confirms the value in this approach as well as its potential applicability to biocontrol worldwide. As more countries and regions continue to adopt, adapt, and expand the system, the prioritization of weeds for biocontrol will become increasingly impartial, credible, and efficient.

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Declarations

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Rachel L. Winston is an environmental consultant specializing in botany, weed biocontrol application, data management, public outreach and education. She curates the database "Biological Control of Weeds: A World Catalogue of Agents and Their Target Weeds."

Mark Schwarzländer is a professor of entomology at the University of Idaho, USA. His research focuses on all aspects of classical biological control of weeds of Eurasian origin in western USA grasslands.

Hariet L. Hinz is the director of CABI in Switzerland as well as the leader of the Weed Biological Control Program. She has 25 years of experience in classical biological weed control, including studies on the rearing, biology, host specificity and impact of herbivorous insects.

Paul D. Pratt is a research leader for the USDA's Agricultural Research Service and has 25 years of experience in the development and implementation of weed biological control programs.